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## Large area printed three-dimensional optical metamaterials

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### ABSTRACT

Metamaterials are engineered materials where artificial properties like negative refractive index, zero-index, artificial magnetism, perfect absorption, and others have been demonstrated. Various two-dimensional metamaterials were fabricated using conventional lithographic techniques. In order to qualify metamaterials as true materials that enables curving out real devices, one need to develop three-dimensional metamaterials. However, fabrication of three-dimensional metamaterials based on conventional electron and ion beam lithography is very tedious. Although this method provides the necessary submicron resolution and excellent control over the in-plane geometries, its practical use is restricted to overall lateral dimensions of <100s of microns. This size limitation, taken together with the complexity of the lithography tools and their extremely slow patterning speeds, makes this technique poorly suited to requirements for realistic applications in superlenses, photonic components or others, where cost, throughput, area coverage, and long range uniformity are important considerations. Alternative approaches to 3D nanofabrication, such as those based on colloidal self-assembly, interference lithography, and two photon polymerization based direct laser writing lack the ability to embed multiple metal/dielectric layers over a 3D space. Nanoimprint lithography and various forms of soft lithography, in their standard embodiments, offer the necessary resolution, but they do not form 3D structures easily. We developed a nanotransfer printing method that is directly applicable to fabrication of 3D metamaterials with excellent optical characteristics, in ways that are scalable to arbitrarily large areas and compatible with manufacturing. We use the resulting methods to fabricate 3D near-infrared negative index metamaterials with 11-layers and sub-micron unit cell dimensions, over areas > 75 cm<sup>2</sup>, corresponding to >105 x 105 unit cells, all with excellent uniformity and minimal defects. With further modifications in material choice and deposition process, the optical response is scaled down to the visible domain. Optical devices like infrared detectors, biosensors, camouflage, and display elements are developed based on these large sheets of metamaterials.